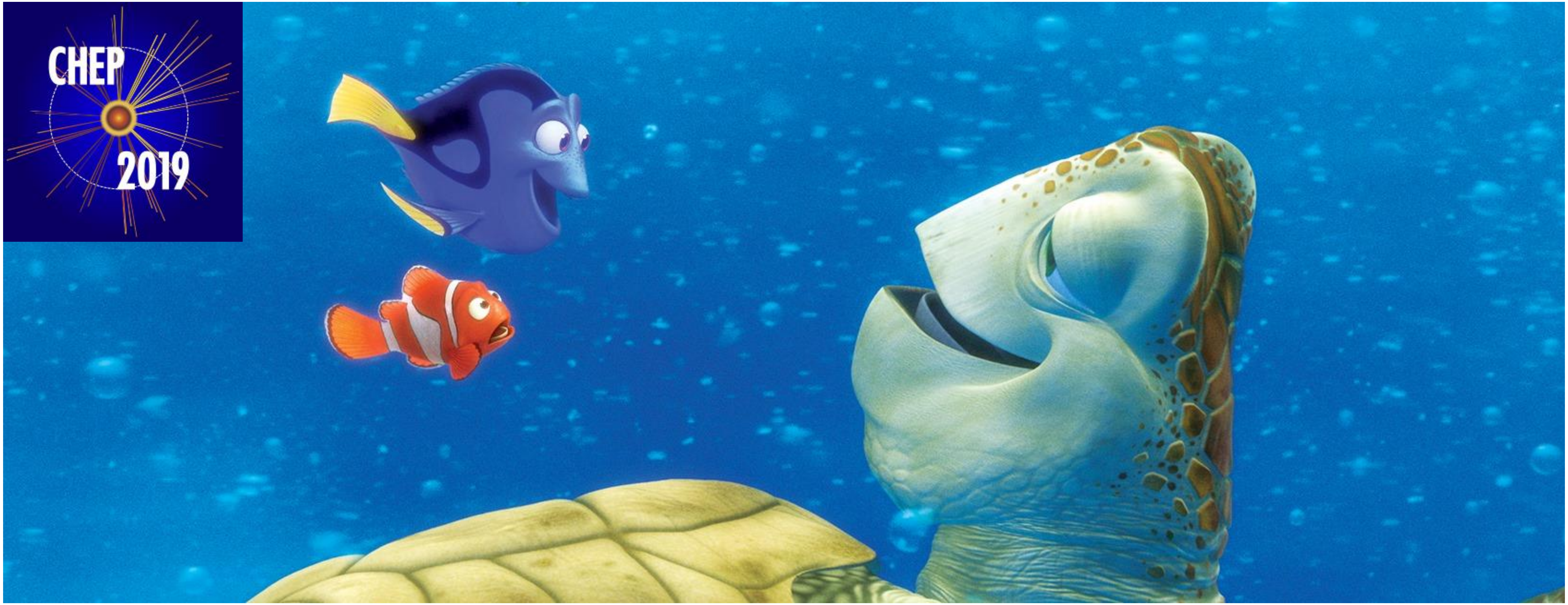

Strategies for detecting long-lived particles at LHC experiments

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Instituto de Física Corpuscular, UV – Valencia

5 November 2019 Adelaide Convention Centre

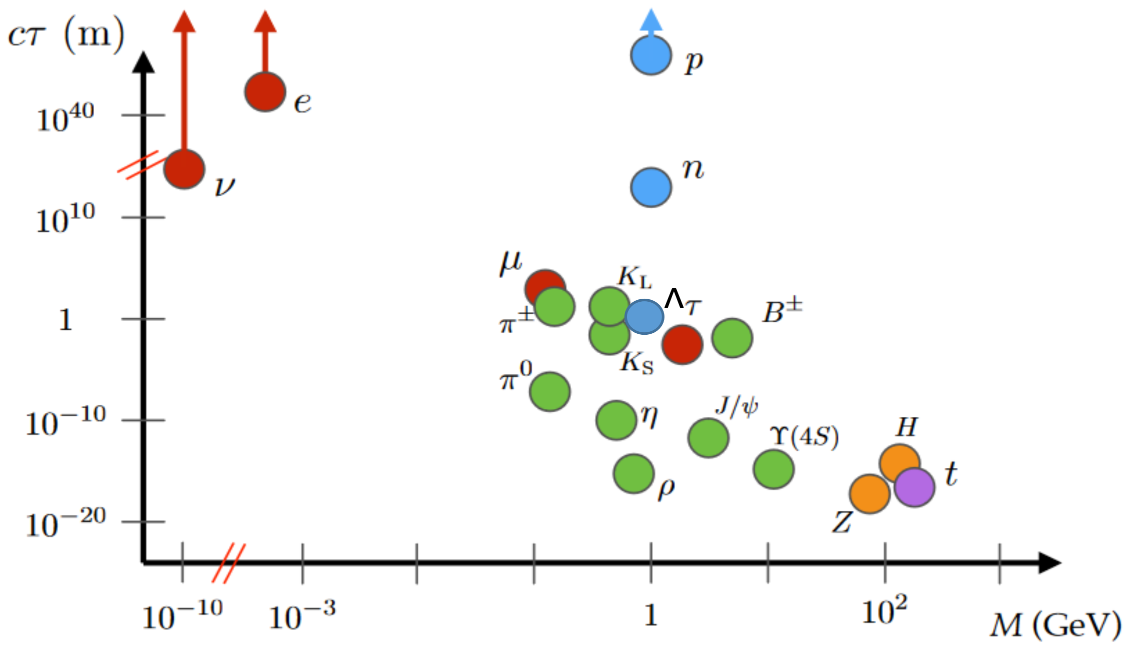
Long Living Particles (LLPs)

- LHC experiments (ATLAS, CMS, LHCb)
  - SM LLPs
  - BSM/NP LLPs
- Dedicated experiments for BSM/NP LLPs
  - MoEDAL, milliQan, MATHUSLA, CODEX-b, and FASER
- Experimental challenges
- Detection strategies and upgrades

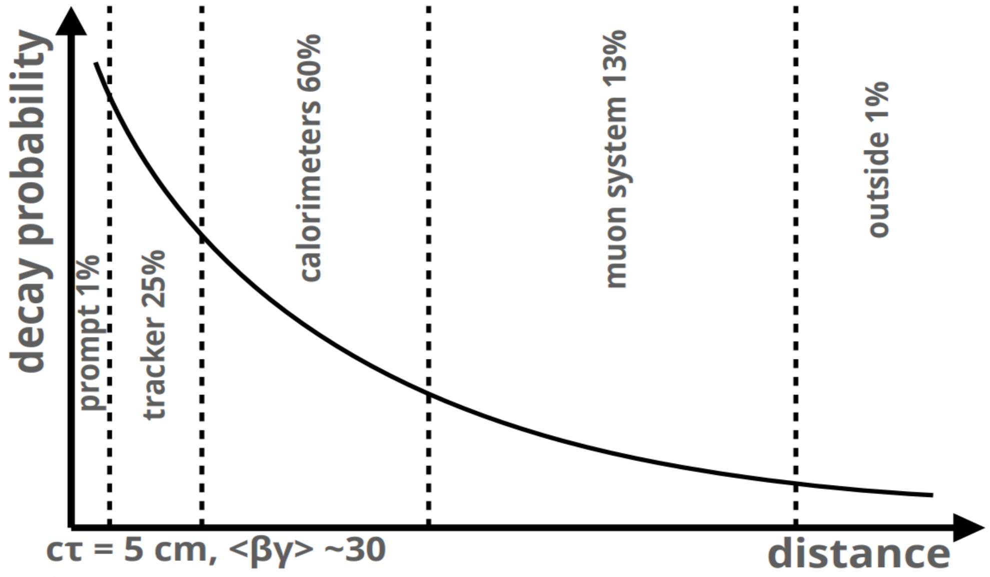
SM Long-Lived Particles (LLPs)

Standard model (SM) LLPs: SM signature of LLPs in LHC experiments

from the Z boson ($\tau \sim 2 \times 10^{-25}$ s) through to the proton ($\tau \sim > 10^{34}$ years) and electron (stable).



[Extended from **arXiv:1903.04497**]

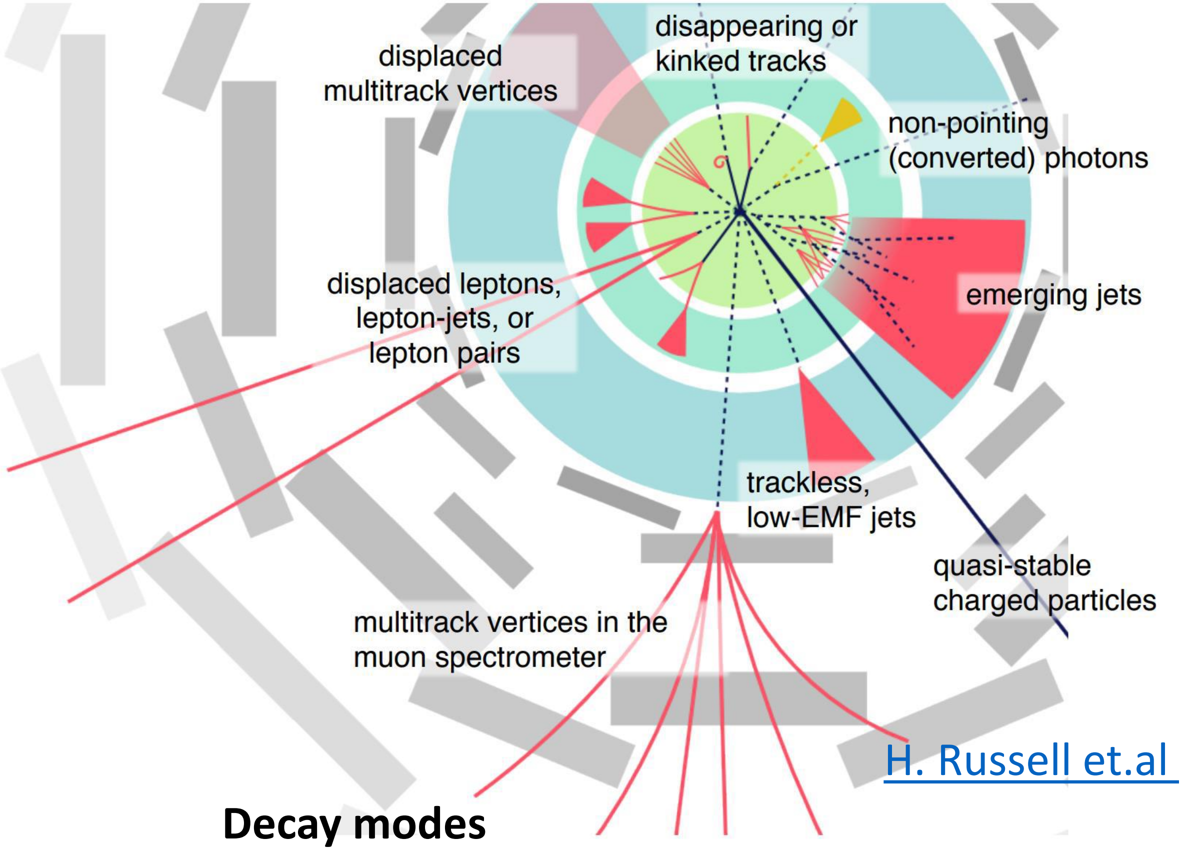


[H Russel , R Rosten@LLP5]

BSM / NP Long-Lived Particles (LLPs)

Beyond standard model (BSM): plethora of different models: detailed community white-paper - [arXiv:1903.04497]

- BSM / NP LLP Searches in LHC experiments ATLAS, CMS, and LHCb
- Dedicated experiments MoEDAL, milliQan, MATHUSLA, CODEX-b, and FASER



H. Russell et.al

Simplified Model Framework

Umbrella Model categories under
- **Supersymmetry-like theories**
- **Higgs-portal theories**
- **Gauge-portal theories**
- **Dark-matter theories**
- **Heavy neutrino theories**

Production modes
- **Direct-Pair Production**
- **Heavy Parent**
- **Higgs**
- **Heavy Resonance**
- **Charged currents**

Decay modes
- **Di-photon decays**
- **Single-photon decays**
- **Hadronic decays**
- **Leptonic deecays**
- **Semi-leptonic decays**
- **Flavored leptonic decays**

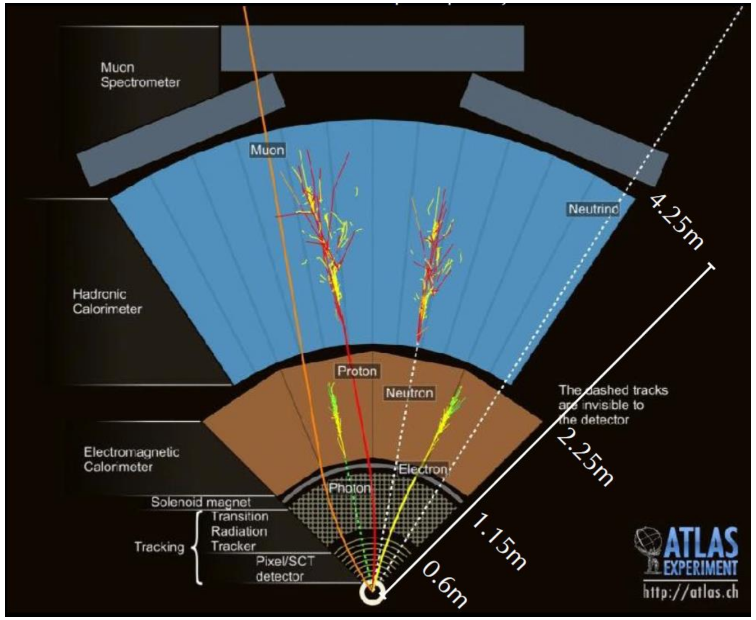
BSM/NP LLP searches and results

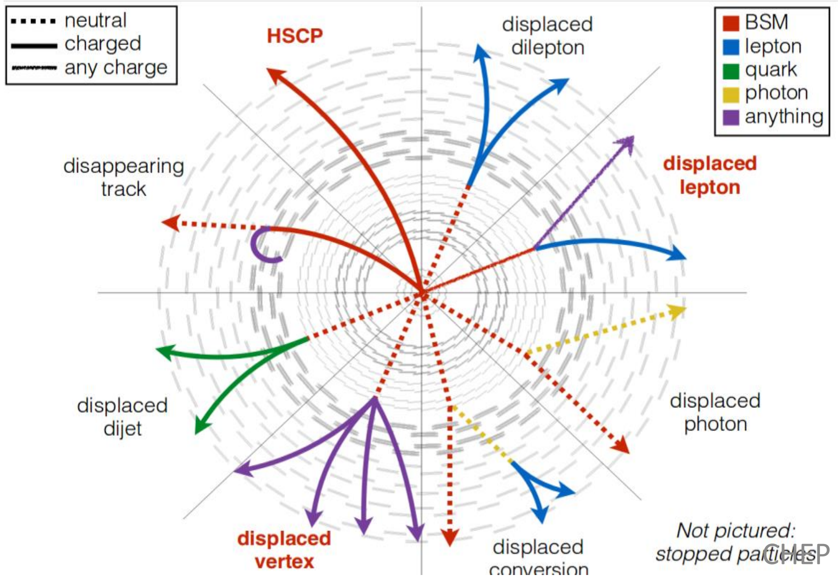
- ATLAS/CMS primarily designed/optimized for prompt particles, not new LLP‘s

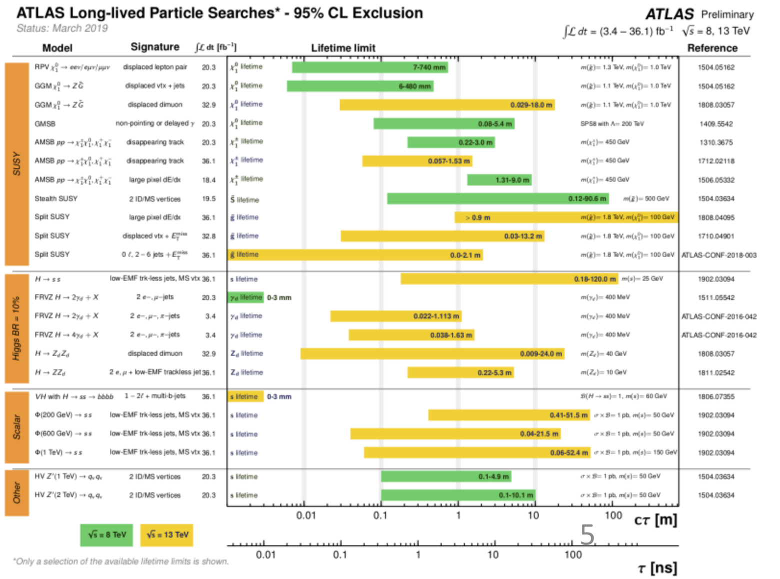
  ➢ Still there have been searches leading to limits (Fig)

  For more details on results and searches :
  List of results - [1] [2]

- Strong focus on NP LLPs in Run 3 and HL-LHC
  ATLAS / CMS Master list for HL-LHC [3]







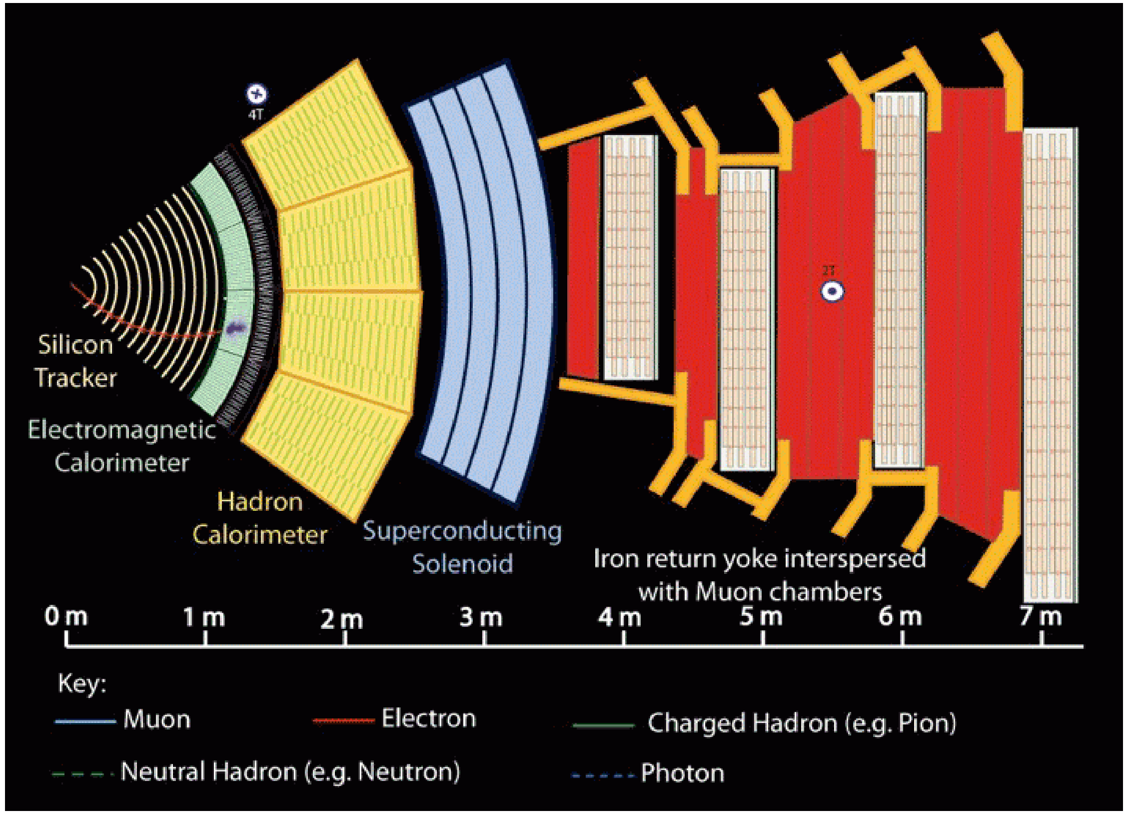
Experimental challenges: SM LLPs measuremets

Reference [1]

Challenge for SM LLP measurements

- Decays outside Vertex or Inner tracking detectors
- Majority of L1 and HLT1 triggers look for signatures in vertex detectors and Inner trackers
- Many particle flow dependent reconstruction techniques transvers outwards from interaction points (L1 and HLT1)

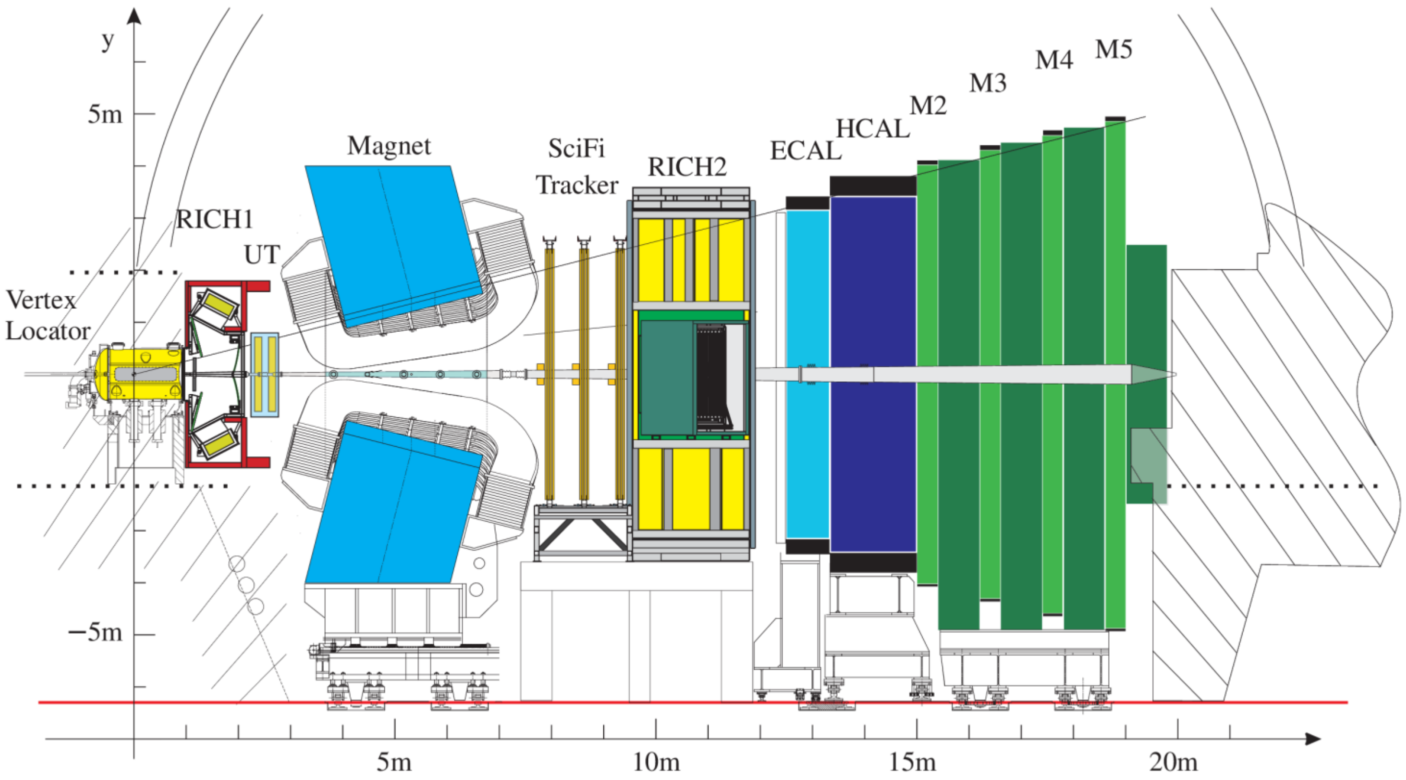
=> Heavy statistical price in some cases

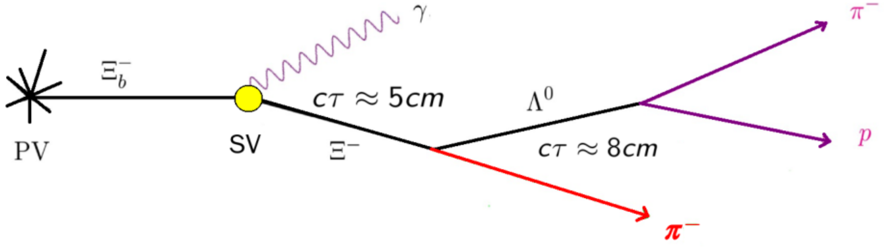


SM LLPs in LHCb

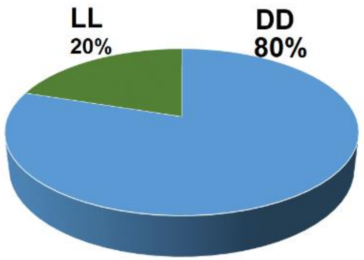
- In LHCb context, SM long-lived: $\mathbf{K_s}$ $\mathbf{\Lambda^0}$, $\mathbf{\Xi^-}$.
- ($\tau \sim 10^{-11} - 10^{-10}$ s) x c = 3 mm – 3 cm.
- Typical boost: γ ~10-100 → mean flight distance 3cm to 3m.
- Narrow decay width due to small phase space and CKM suppression (s → u transitions)

LHCb upgrade TDR – [LHCB-TDR-018]

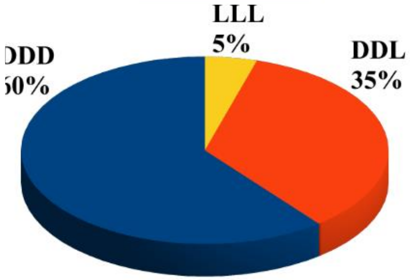


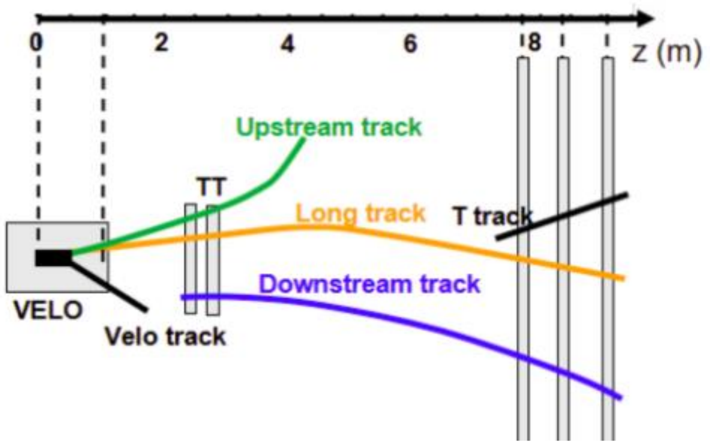


$\Lambda_b \to \Lambda\gamma$



$\Xi_b^- \to \Xi^-\gamma$





[1. L. Henry, L M Garcia, A. Oyanguren, B Jashal]

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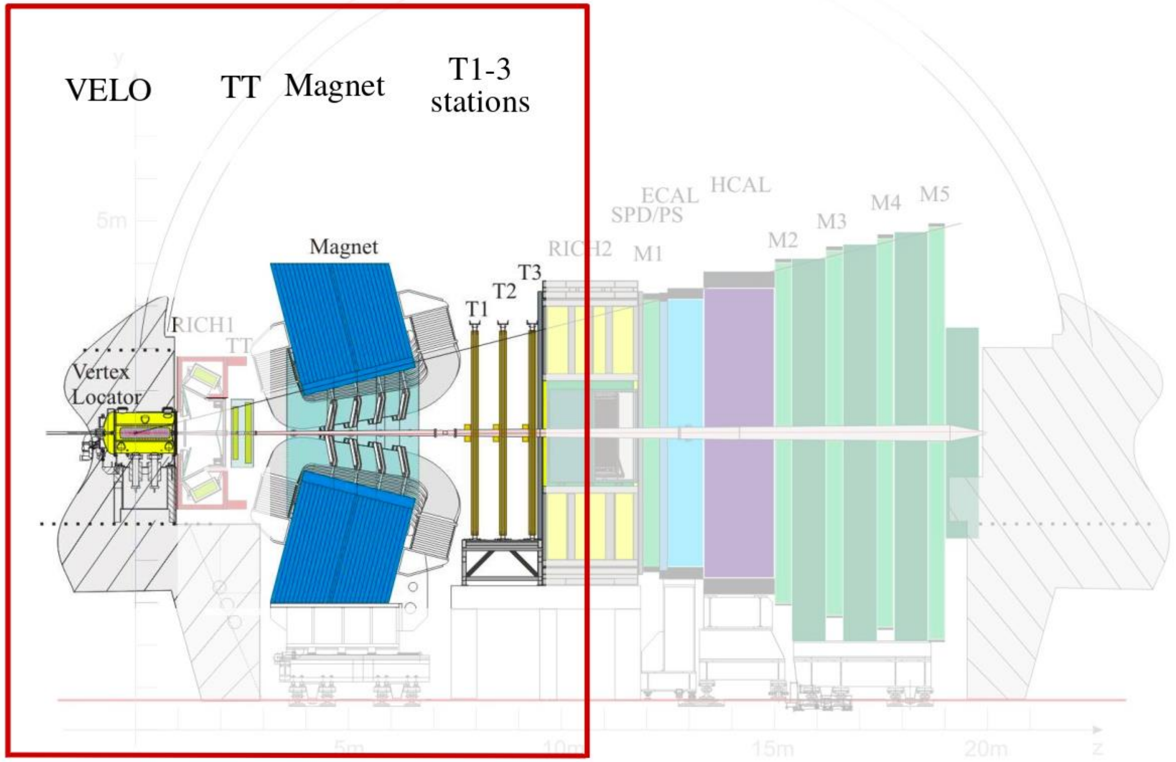

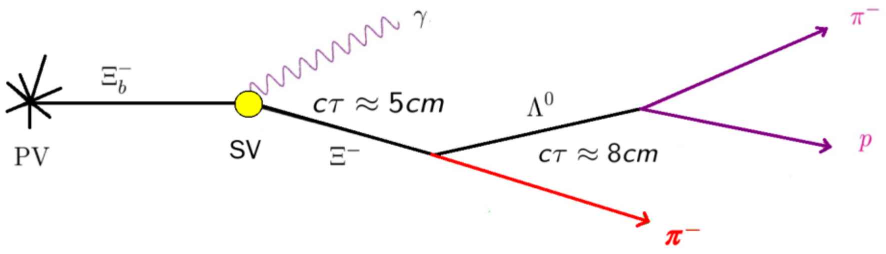

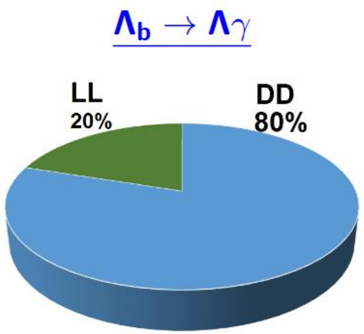

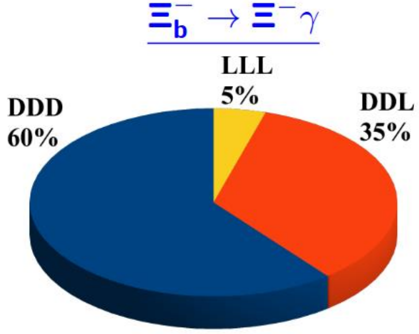

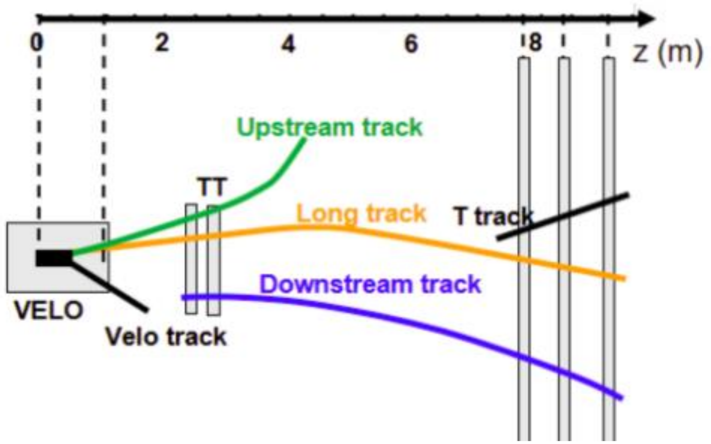

[1. L. Henry, L M Garcia, A. Oyanguren, B Jashal]

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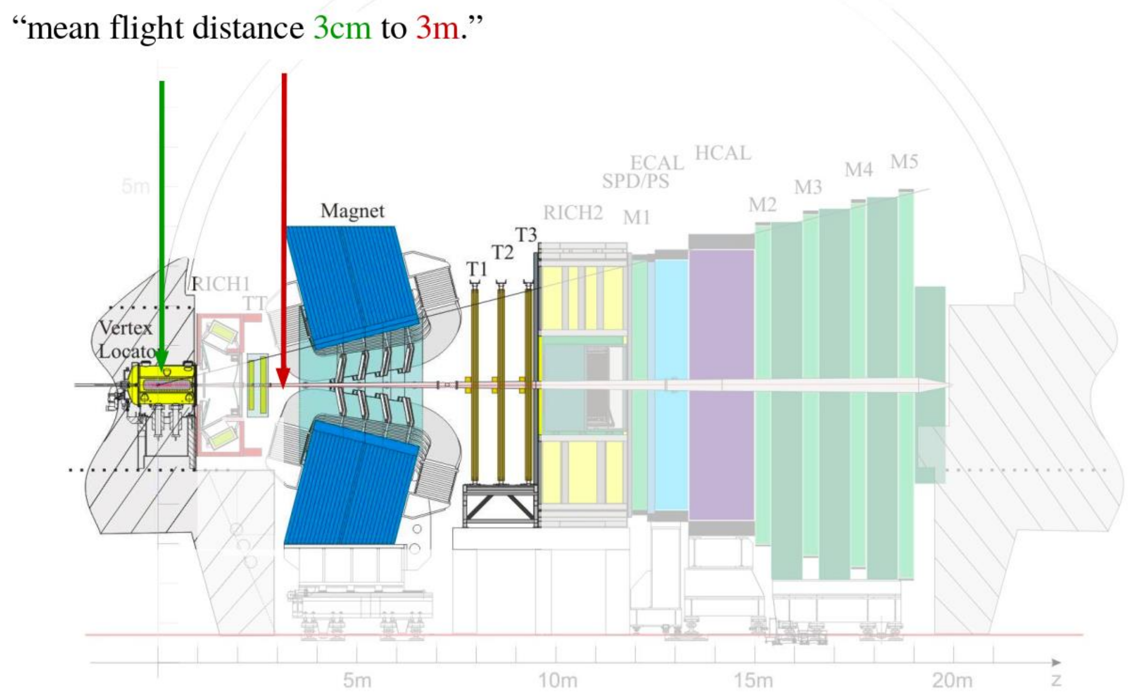
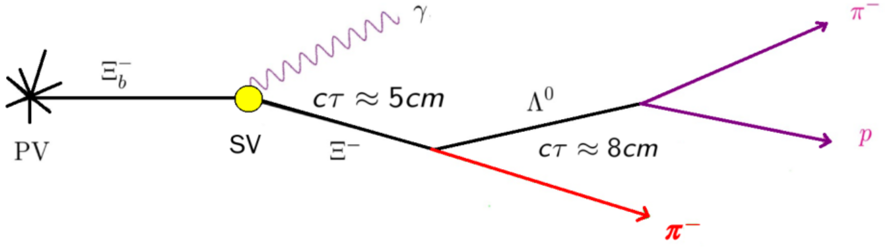
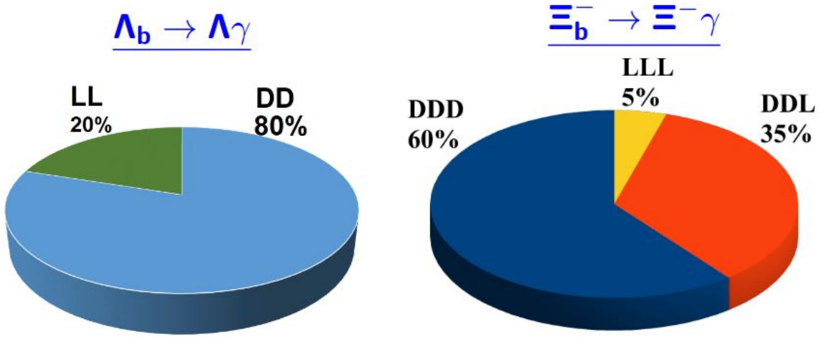
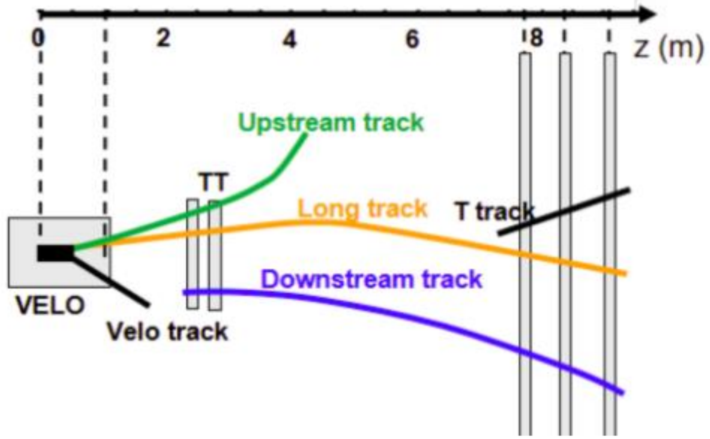






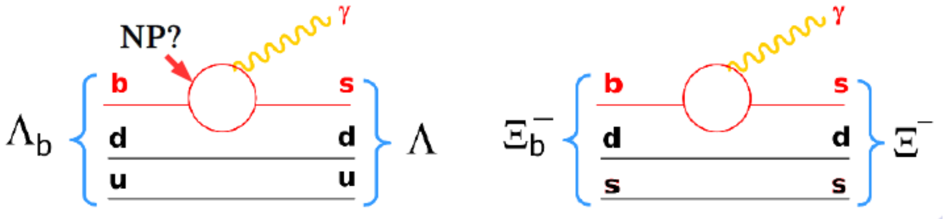


[1. L. Henry, L M Garcia, A. Oyanguren, B Jashal]

SM LLPs in LHCb: Physics case: implications

e.g. photon polarisation in radiative decays

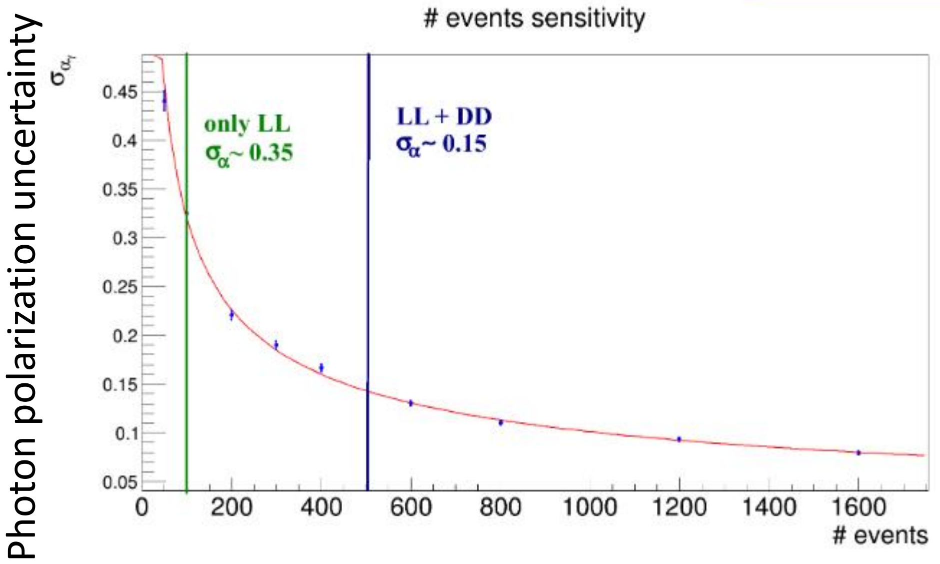
- ➢ b→ s transitions occur through a virtual loop (penguin diagram).

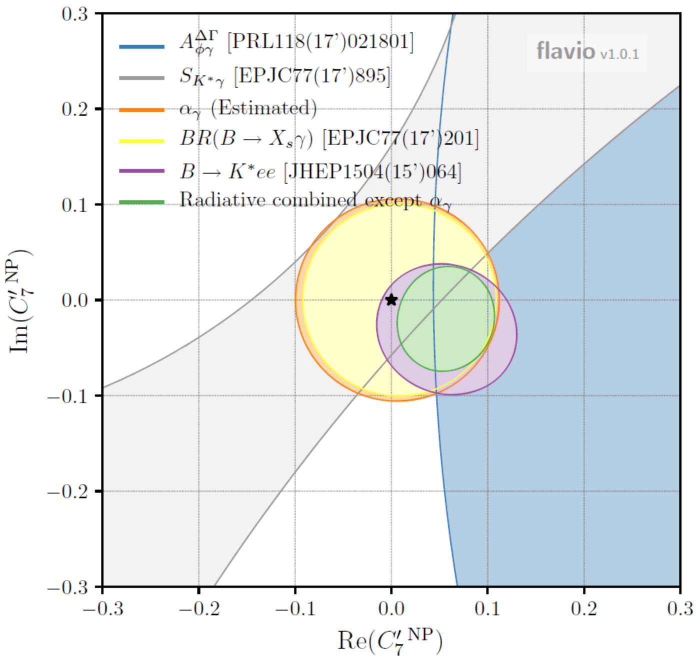


- ➢ Amplitude can be developed using Wilson coefficients C7 and C7'.
  - Photon is predominantly left-handed in the SM → C7'

$$\mathcal{H}_{eff} = -4\frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left(\underbrace{C_7 O_7}_{\text{left}} + \underbrace{\cancelto{0}{C_7' O_7'}}_{\text{right}}\right)$$

- ➢ New physics inside of the loop could have a different structure
  → apparition of right-handed photons?
- ➢ Measurement on baryon decays.
- ➢ Complementary with current tensions on C9.





DOI: 10.1140/epjc/s10052-019-7123-7

Experiment challenges in BSM/NP searches of LLPs in LHC

- Signature based searches where NP LLP signatures not well defined or not known or can not be accommodated in the triggers
- Standard reconstruction algorithms may reject events or objects containing NP LLPs precisely because of their unusual nature
- Significant differences in object reconstruction algorithms and techniques
  - Dedicated reconstruction of tracks, jets, leptons, or other objects.
- MC may not accurately model backgrounds for NP LLP searches

Upgrades and outlook

in parallel with theory developments

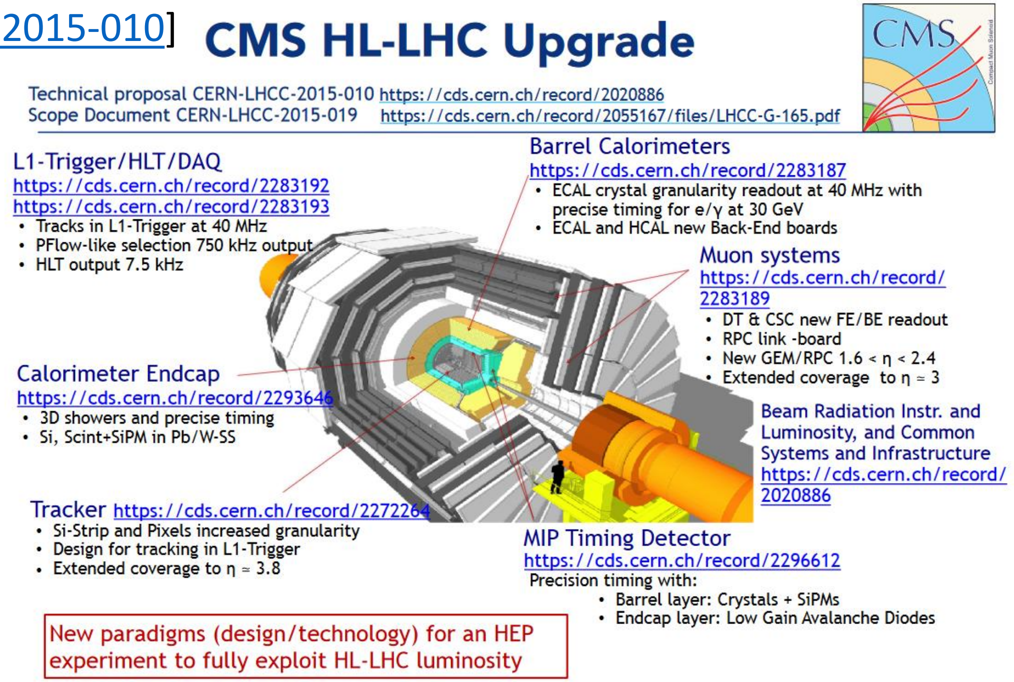
- Detector upgrades:
- Triggers and Real Time Analysis
- Reconstruction and analysis techniques
- Computing frameworks and platforms

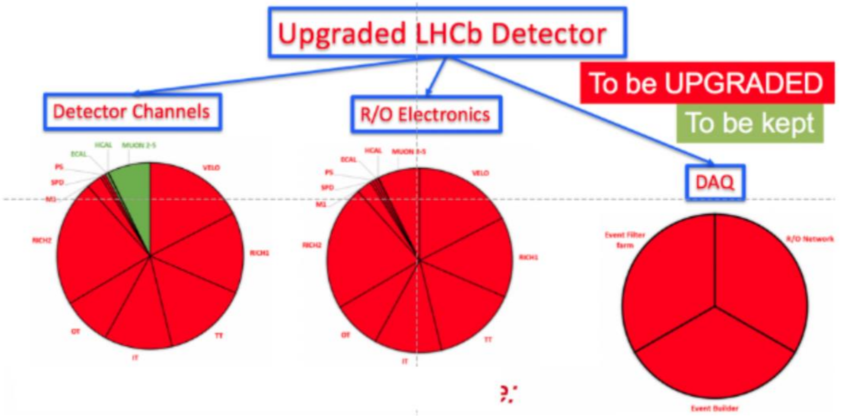
Detector upgrades:

Upgrades

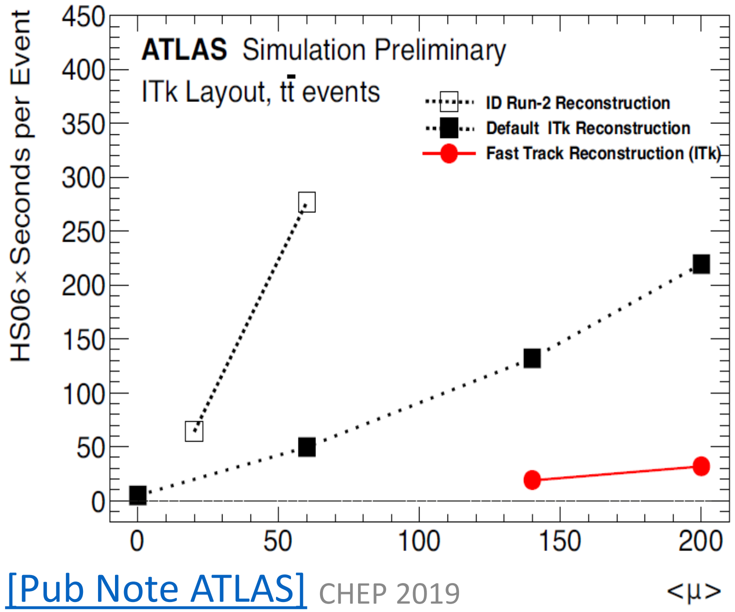
- Tracker, Calorimetry , Muon Systems , Timing detector, Trigger
  - ➢ Improved physics reach
  - ➢ Improved detector geometry
  - ➢ Detector material maps
  - ➢ New detector layers and technologies (timing)
    e.g.   Glueballs from Higgs boson decays
    neutralino and chargino pair production in GMSB

[CERN-LHCC-2015-010]

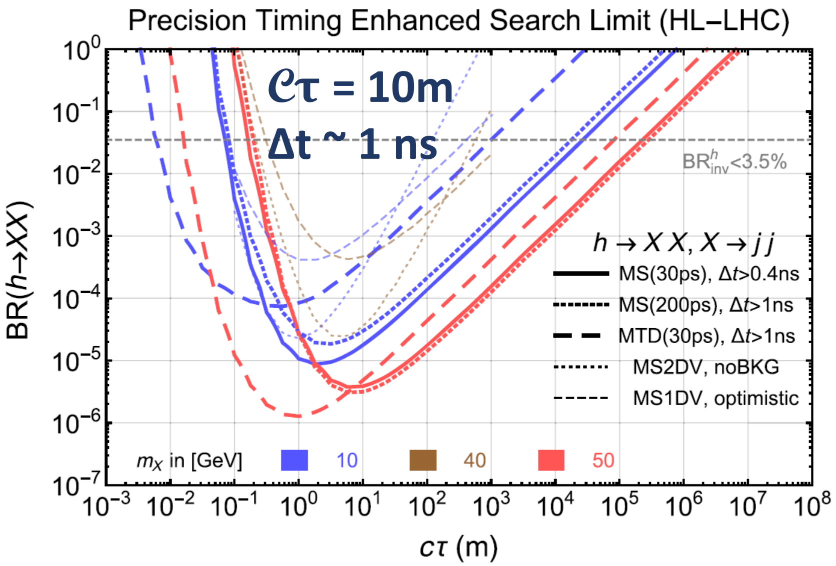




[LHCB-TDR-017]



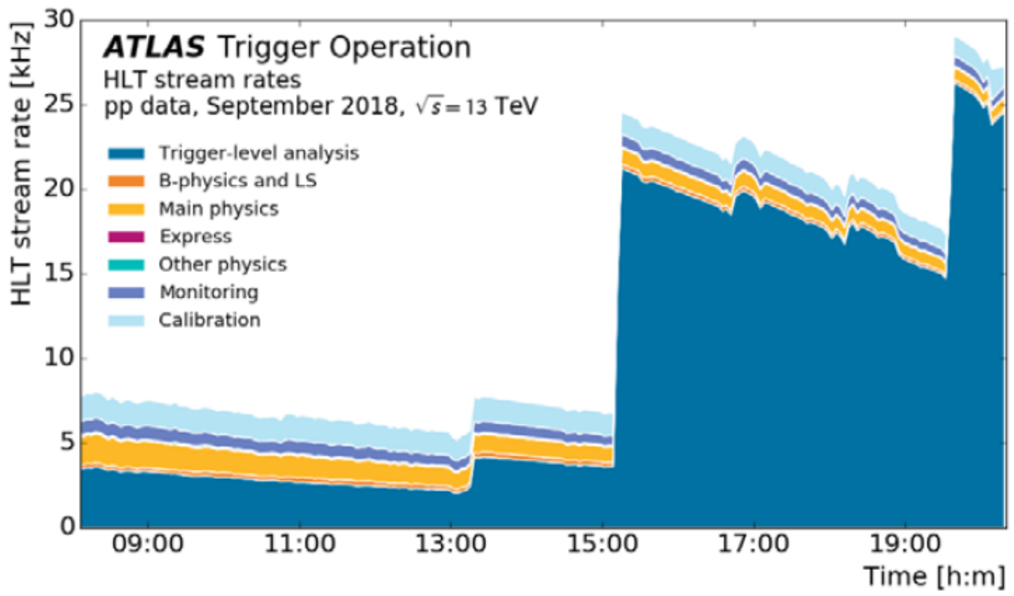
[Pub Note ATLAS]



[DOI: 10.1103/PhysRevLett.122.131801]

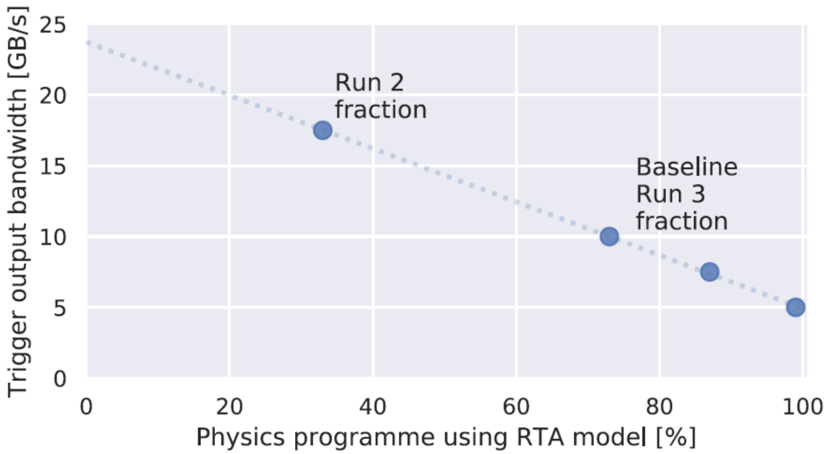
Triggers

- No dedicated L1 triggers for LLPs except, only few exceptions
  - Triggering is expensive: must fit within computing constraints
  - Need for well defined signatures
  - Performance gains in trigger algorithms == more scope for additional signatures in the triggers



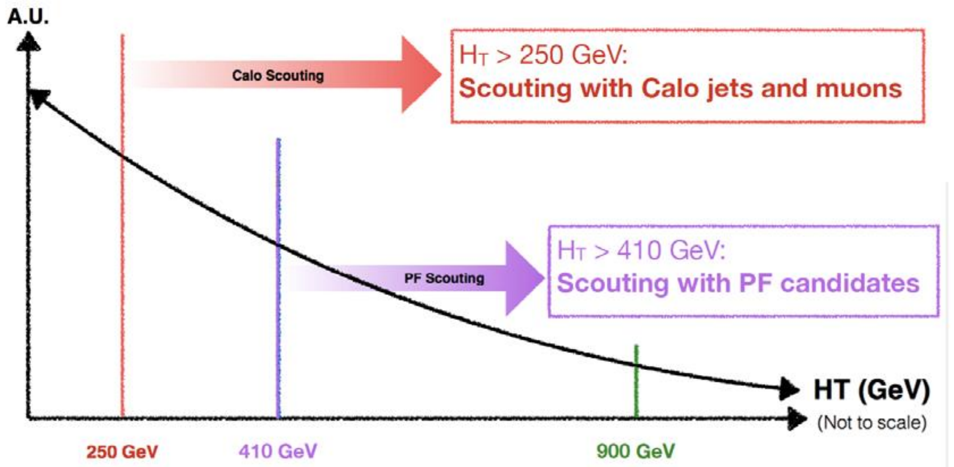
[ATLAS, PRL 121 (2018) 081801]

- Real Time Analysis models
  - RTA in LHCb
  - Scouting in CMS
- TLA(Trigger-object Level analysis) ATLAS



[PRL 117 (2016) 031802]

- Data parking (e.g - CMS B Physics run in 2018 – adiitional 12 B events = 6KHz to tape)



[CMS-EXO-11-094]

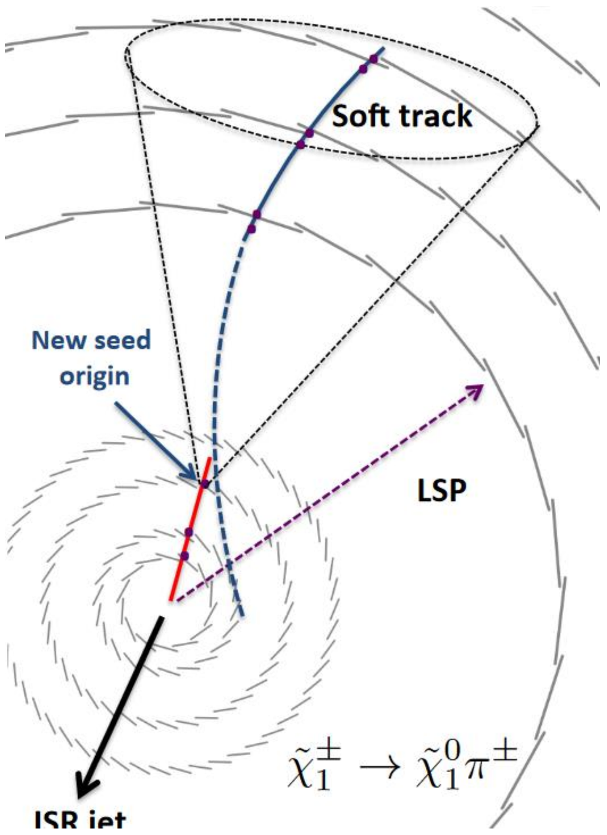
Reconstruction and analysis techniques

- Avoid early rejection of LLP objects.
- Track reconstruction optimization for LLPs
- Extending algorithms like Downstream(in LHCb) and b-tagging (CMS and ATLAS) for improving secondary vertex reconstruction
- Effective utilization of new detector layers like timing for faster reconstruction and extending LLP searches
- Background rejection using Jet cleaning

[ML working group summary for LLPs]

ML based LLP analyses e.g. :

- ML for finding displaced jet IDs (ATLAS) (using MLP)
- Tagging for disappearing tracks (CMS) (using BDTs)
- ML approaches for vertex reconstruction(tracker, calorimeters, b-tagging)



[long-lived higgsinos in ATLAS: LLP workshop]

[Tracking performance for LLPs]

Data-driven method for measuring the efficiency track reconstruction efficiency of LLPs in LHCb

Long tracks

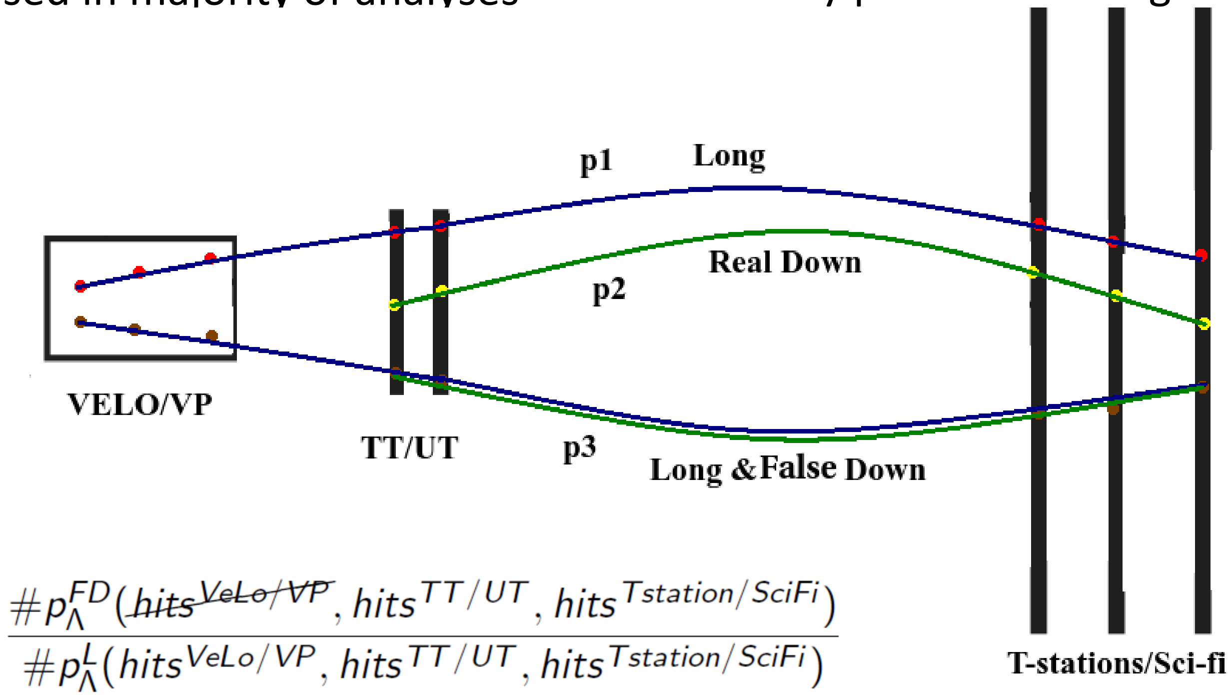
Hits at least in VELO and T stations

Used in majority of analyses

Downstream tracks

Hits in TT and T stations (not in VELO)

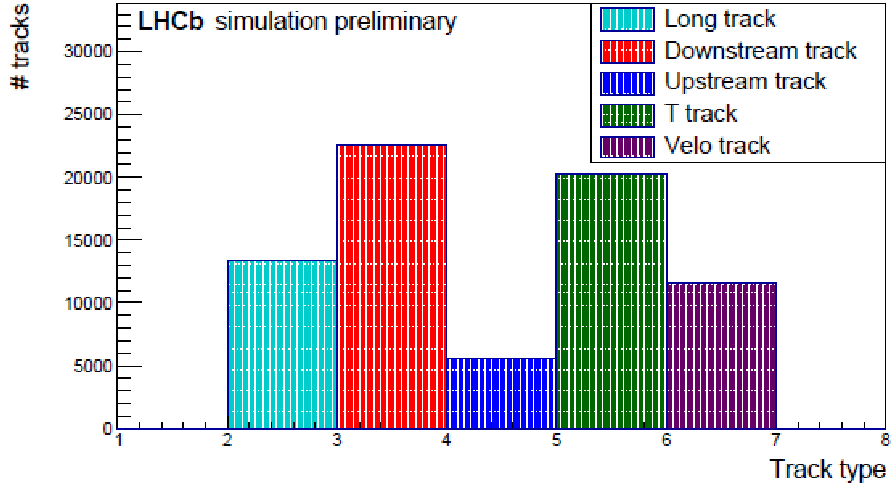
Decay products of long-lived particles

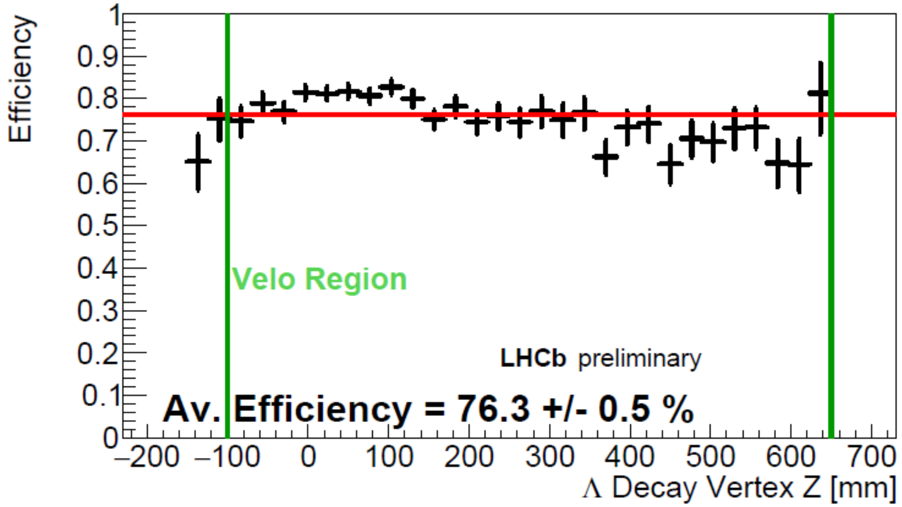


$$\epsilon = \frac{\#p_{\Lambda}^{FD}(\cancel{hits^{VeLo/VP}}, hits^{TT/UT}, hits^{Tstation/SciFi})}{\#p_{\Lambda}^{L}(hits^{VeLo/VP}, hits^{TT/UT}, hits^{Tstation/SciFi})}$$

[Ref 2]

Proportion of each track type in the $\Lambda \to \pi p$ decay



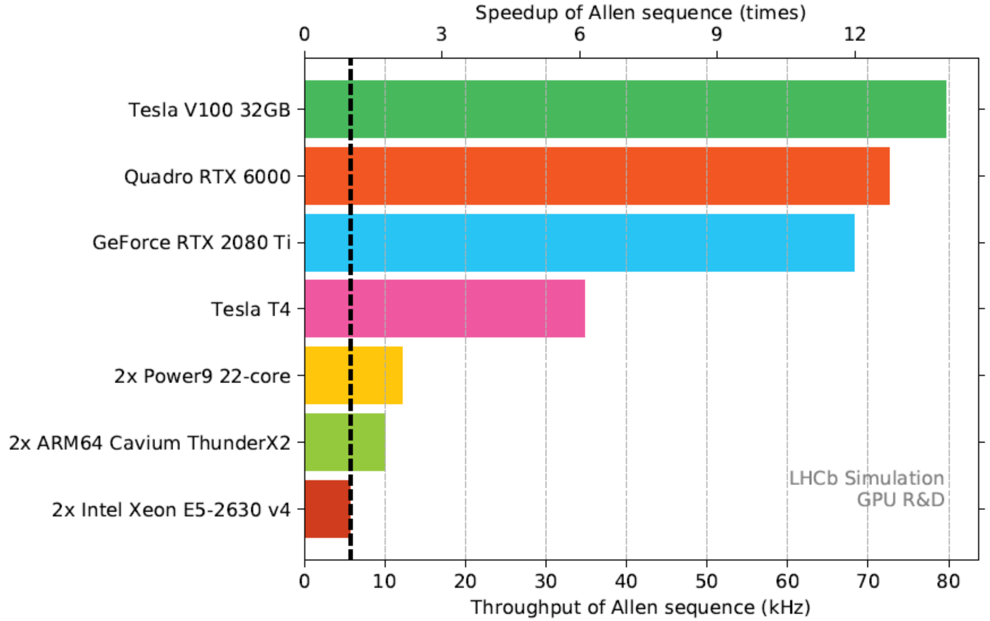


	Efficiency (%)	
	This method	MC Info
Simulation Run II	**77.4 ± 0.7**	74.5 ± 0.3
Real Data Run II	**76.3 ± 0.5**	–
Simulation Run III	**89.4 ± 0.2**	89.7 ±0.1[1]

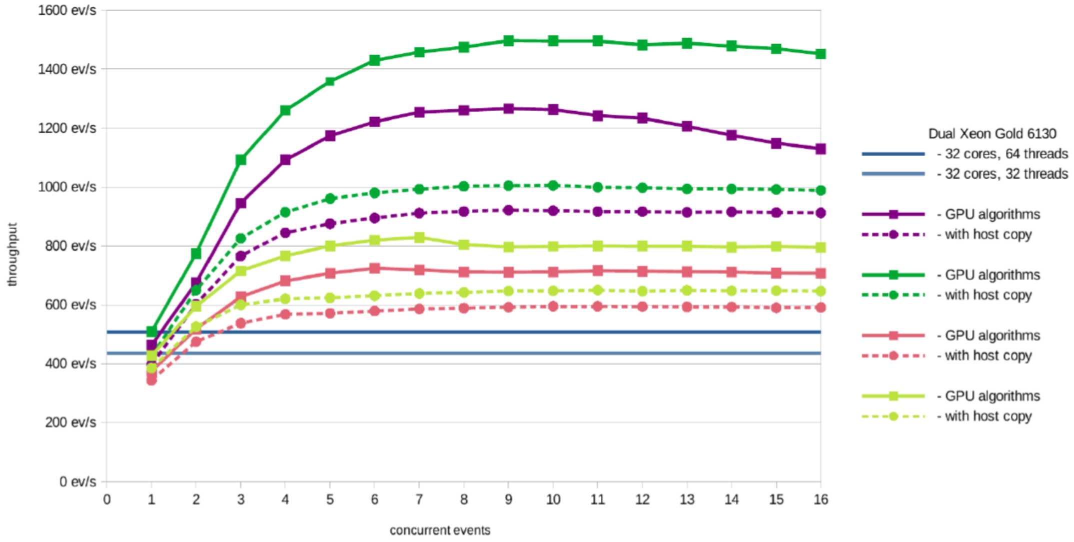
Computing frameworks and platforms

- Adoption of hybrid architectures (x86, FPGA, GPUs, ARM etc) in online and offline computing
  - ➢ Offsetting the saturation of moors law
- Dedicated projects within LHCb, CMS and ALICE to run HLT on GPUs
- Use of FPGAs in L1 triggers in CMS and ATLAS

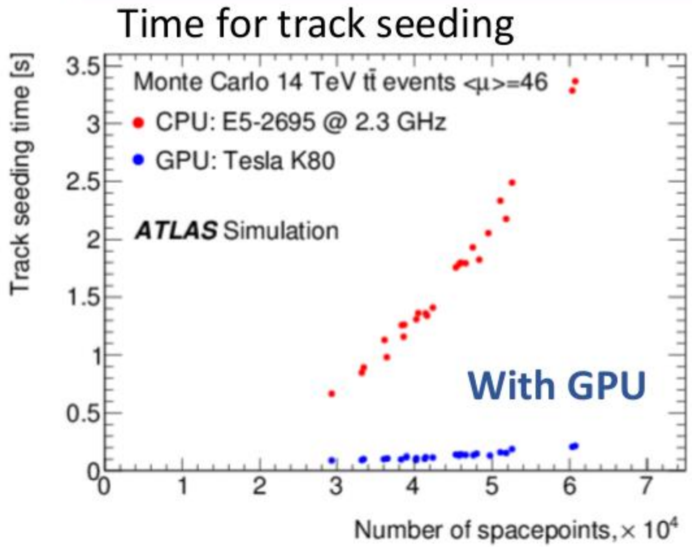
➔ These developments will certainly benefit LLP studies and searches.



[LHCb Allen]



[CMS Patatrack]



Conclusion and outlook:

- LLPs provide a very promising avenue for probing interesting physics properties for SM as well as BSM
- NP LLPs searches in LHC not easy as detectors are designed for searches of promptly decaying NP candidates
- At present all LLP searches and studies are mainly dependent on final states
- Ongoing work in Triggers, tracking, algorithims and plateforms will greatly benifit prospects of LLP searches in LHC experiments.

Thank you